# Low-Cost Optical Terminal (LCOT)

# Initial Test Results Of The LCOT Adaptive Optics System

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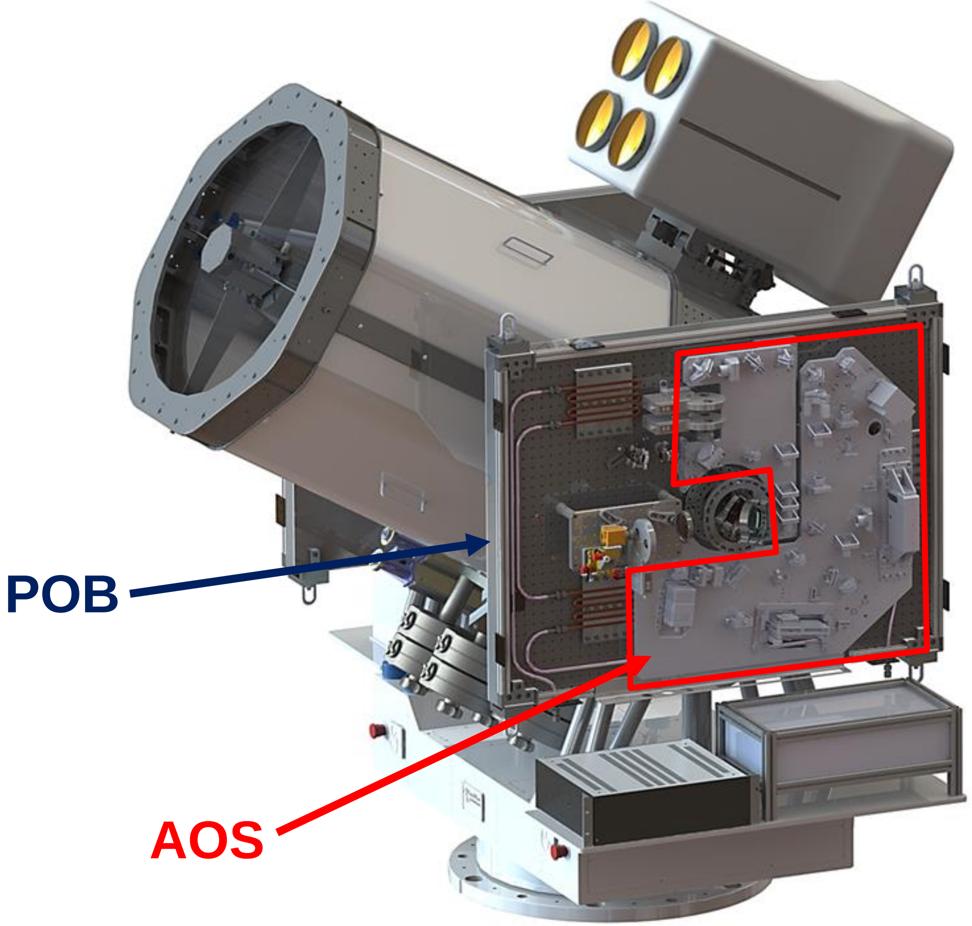
# The LCOT AOS

# Introduction

- LCOT designed to serve TX and Rx for missions at LEO, GEO, and Lunar orbits
- Design philosophy:
  - Modular for high level of reconfigurability between missions
  - COTS
- Located at Goddard Geophysical Astronomical Observatory (GGAO)
- Receive Telescope:
  - PlaneWave Instruments RC700-F12
  - Type: Ritchey-Chretien with Nasmyth access on both sides
  - Diameter 700 mm
  - Focal Ratio: F/12
  - Alt-Az mount
- Port Optical Bench (POB) at Nasmyth
  - Wide Field of View Camera for pointing & tracking
  - Adaptive Optics (AO) system
- Starboard Optical Bench (SOB) at Nasmyth
  - Few or multi-mode fiber
  - No AO
- Transmit Optical Assembly (XOA)



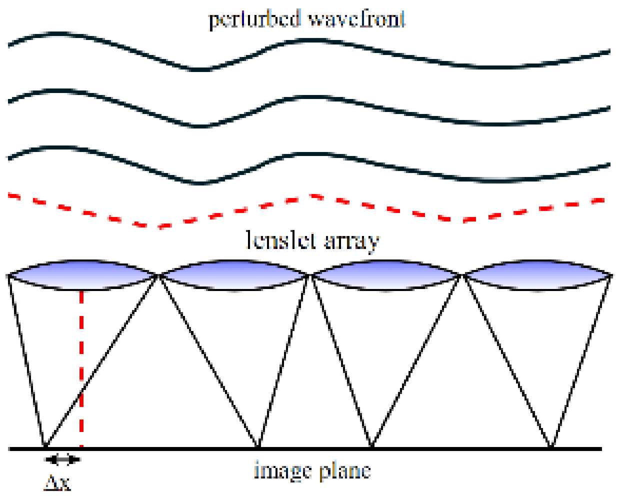
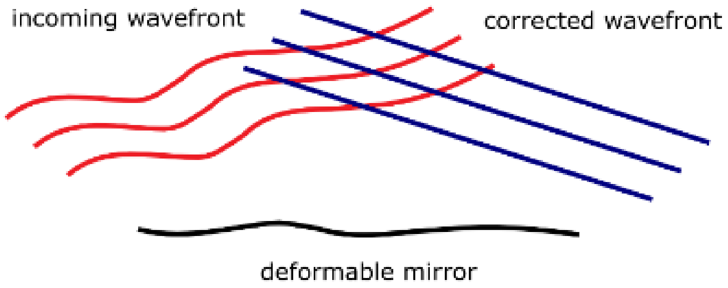
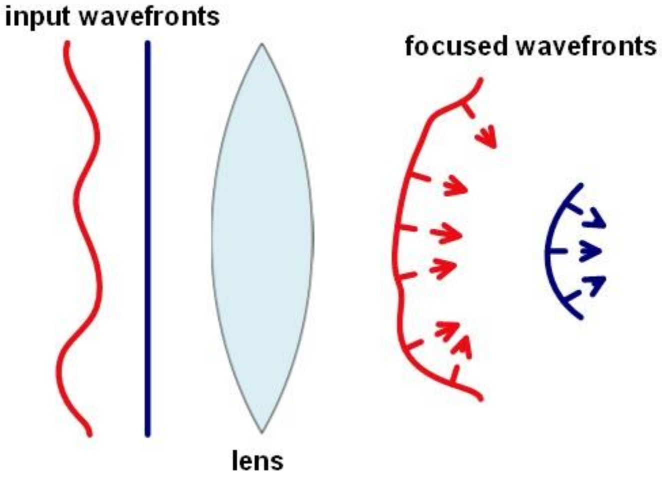
# AO Motivation

- Infrared received signal between 1500 and 1600 nm
- Coherent communication formats to be coupled into an 8-12 µm single mode fiber
- Large telescope + atmospheric turbulence
  - ⇨ Blurry image, large spot, speckle pattern
  - ⇨ Wobbling spot
- Coupling into fiber improved when using Adaptive Optics (AO)
  - Wavefront sensor + DM to correct image wavefront and spot size
  - Tracking system to stabilize spot on the fiber head
- AO system:
  - Measures wavefront distortion caused by atmosphere turbulence
  - Then applies an inverse distortion to a deformable mirror (DM)
  - Cancels out turbulence induced wavefront error
  - Allows signal to be imaged closer to the diffraction limit of the telescope

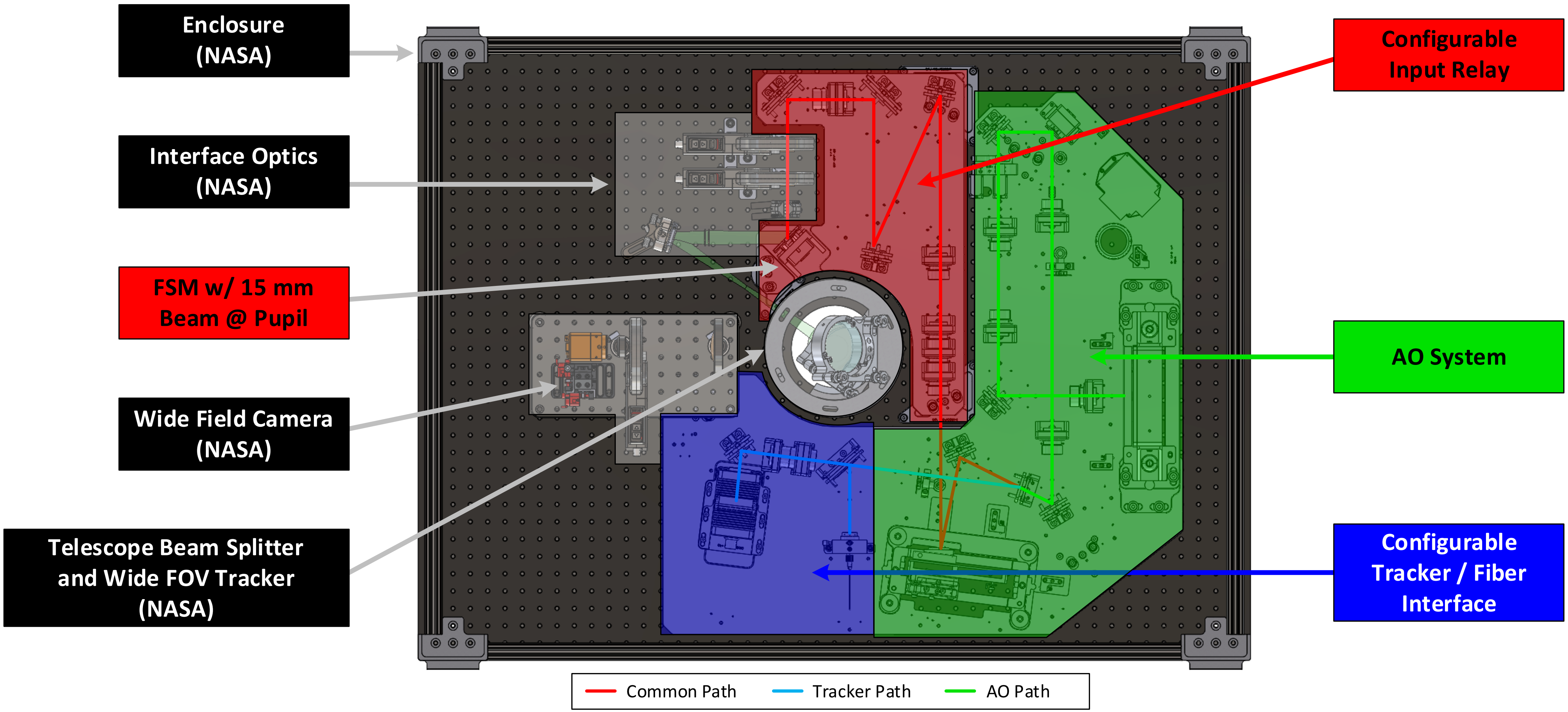
| Atmospheric Parameter | Specification |
|---|---|
| Fiber Coupling Efficiency | 25% |
| Fried Parameter ($r_o$) | $7.5\ cm$ |
| Greenwood Freq ($f_G$) | $109\ Hz$ |
| Rytov Variance ($\sigma_R^2$) | $0.278$ |
| Tilt Greenwood Freq ($f_T$) | $16.3\ Hz$ |

# How AO Works?

- Atmospheric optical turbulence disturbs the amplitude and phase of coherent laser downlink light
- A Shack-Hartman Wavefront Sensor (SH-WFS) detects phase distortions using a microlens array and an infrared (IR) camera
- The Deformable Mirror (DM) corrects phase aberrations by altering transverse path lengths
- The light can now be focused to a sharper point for fiber coupling improvements (improves Strehl Ratio)

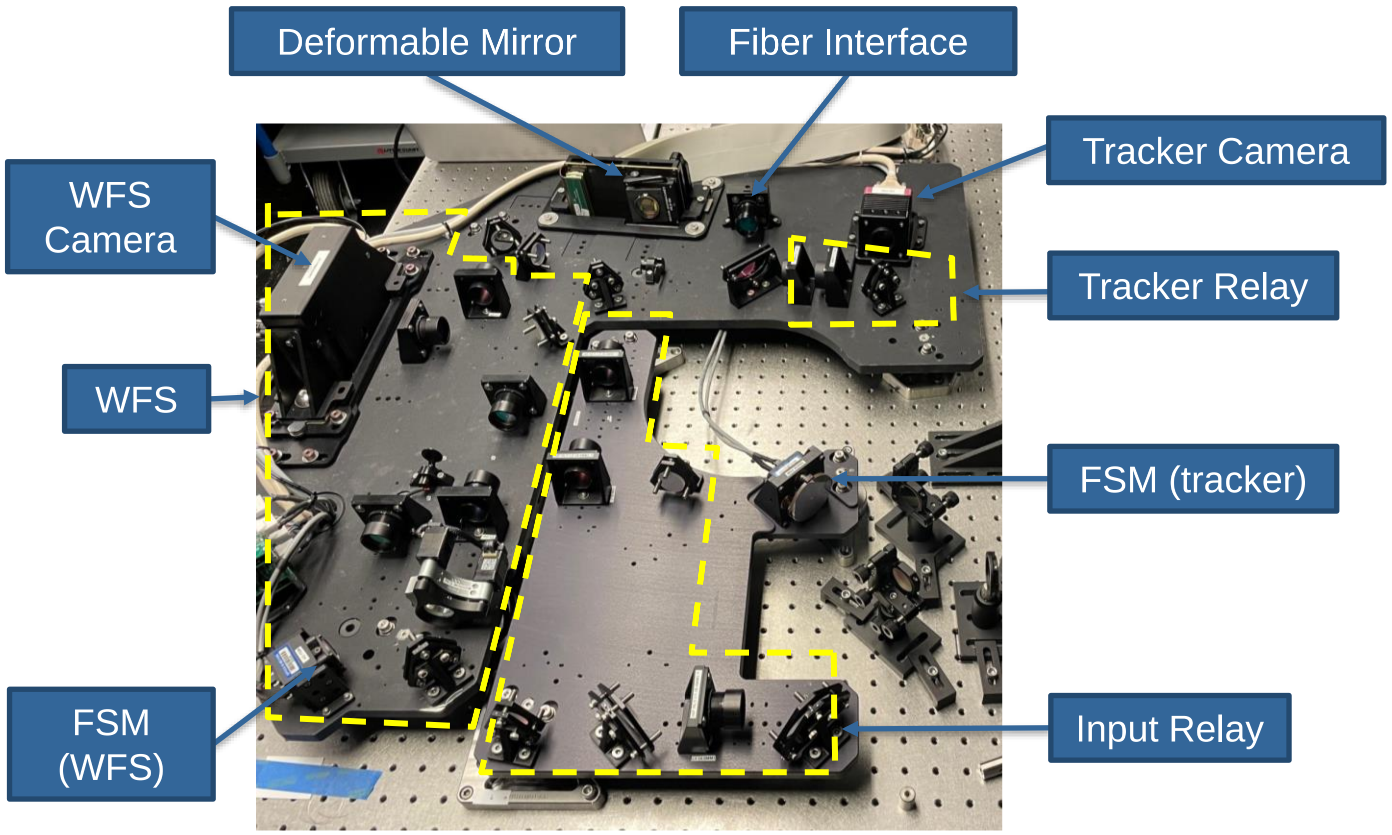
| **Wavefront Sensor (WFS)** | **Deformable Mirror (DM) Compensation** | **Implications for Focusing** |
| --- | --- | --- |
|   |   |   |

# AO Design

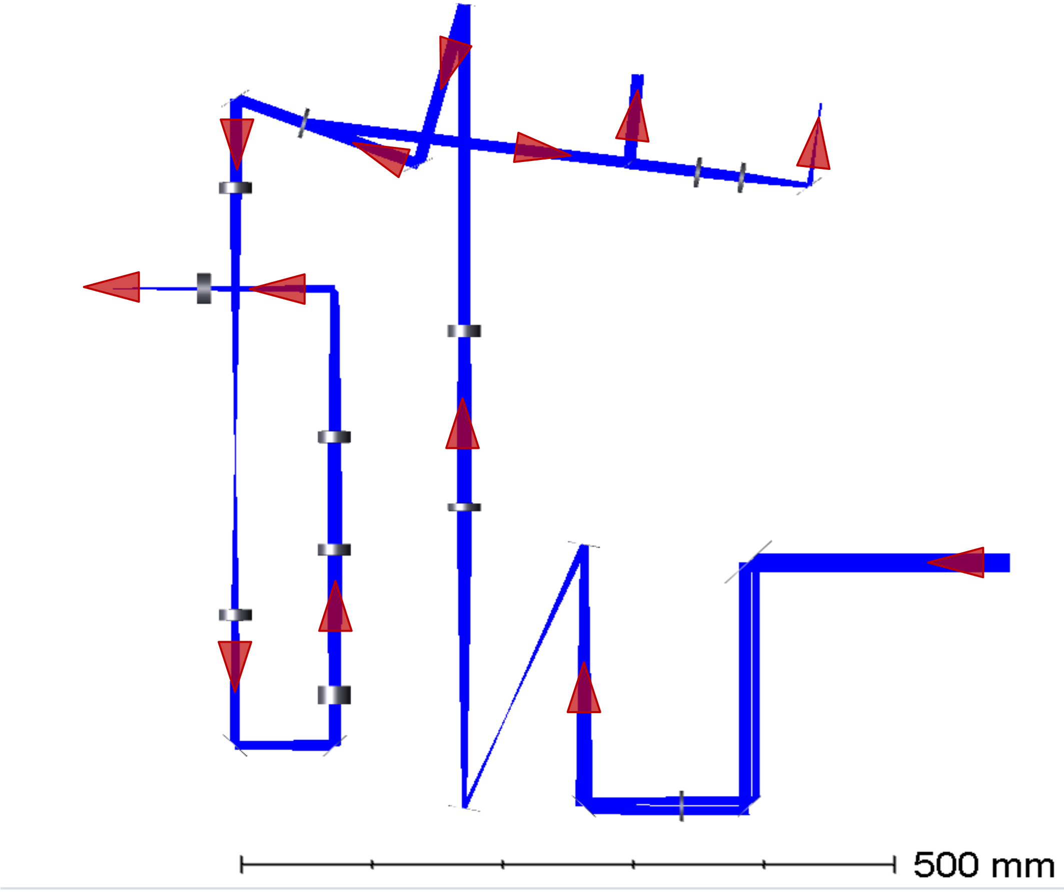


Enclosure (NASA)
Interface Optics (NASA)
FSM w/ 15 mm Beam @ Pupil
Wide Field Camera (NASA)
Telescope Beam Splitter and Wide FOV Tracker (NASA)
Configurable Input Relay
AO System
Configurable Tracker / Fiber Interface
Common Path
Tracker Path
AO Path

# AO Optical Path




## Optical Path



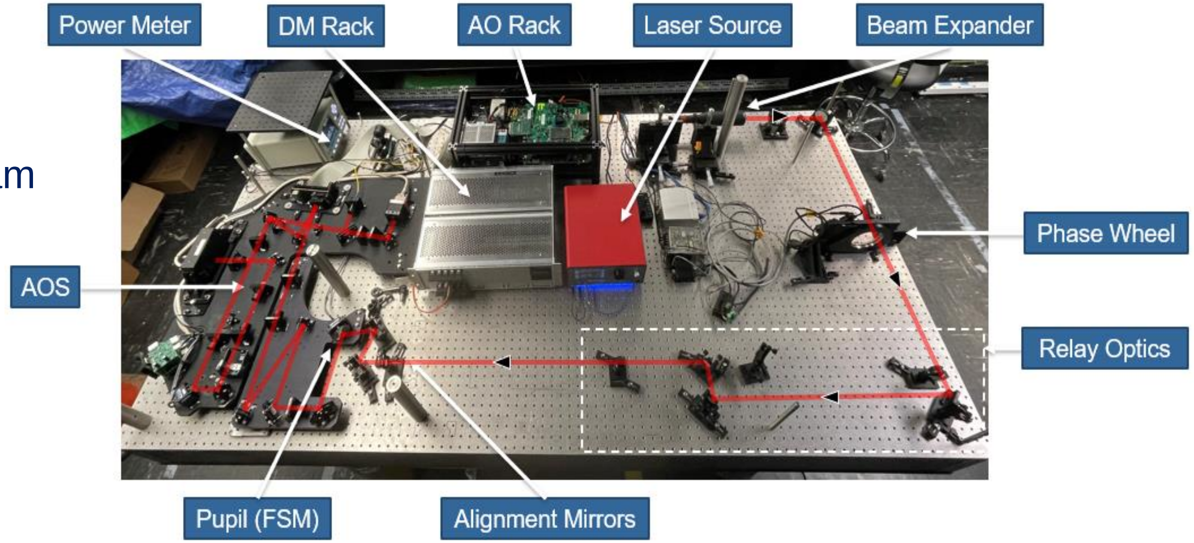
# General Atomics AO System

- Spectral range: 1500 to 1600 nm
- Wavefront sensor:
  - Lenslet array 24 x 24
  - WFS FSM
  - Frame rate: 10kHz
  - Deformable mirror
    - Boston Micromachines 492-DM
    - 16x16 actuators
    - Actuator stroke = 3.6 μm – Pitch = 400 μm
- Tracking system
  - Tracker FSM: 1kHz - ± 1.5°
  - Tracking camera
- Reconfigurable input relay optics
  - 6.4 mm pupil on DM
  - 4 mm pupil on DM
- Pupil registration
  - Tip/tilt window to register beam position DM/WFS
- Non-common path correction
  - Zernike injection to optimize output power from single-mode fiber
- SMF-28 single-mode fiber with F/4 lens system for beam injection

# Laboratory Test Setup

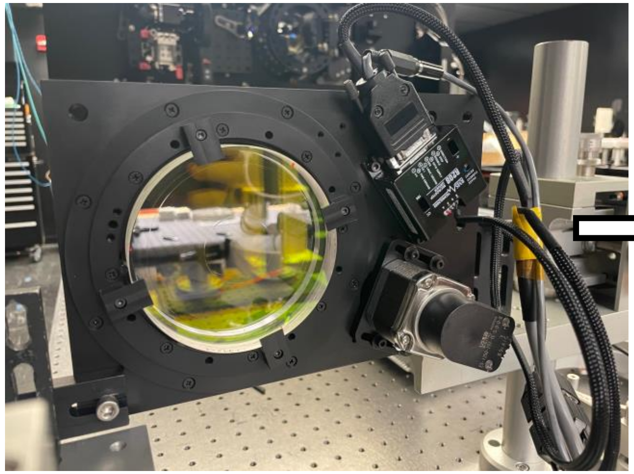
# Laboratory Testing

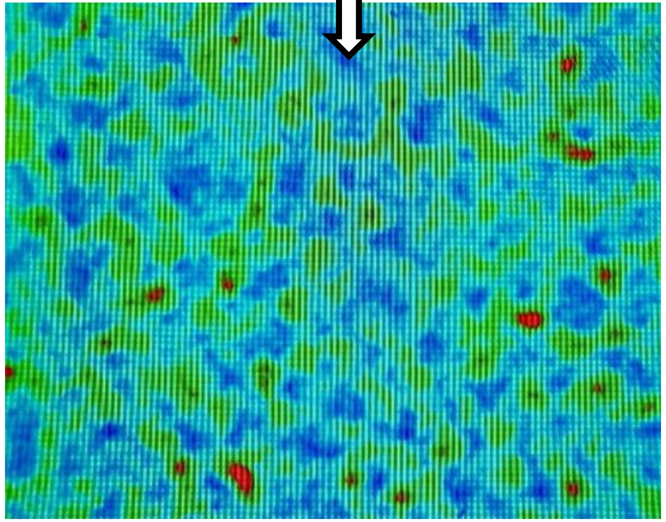
- Objective: Test fiber coupling efficiency by measuring power output and using a phase wheel to simulate air turbulence
- AOS tested at NASA/GSFC in lab
- Test Setup:
  - Laser source λ = 1528 to 1563 nm to create a collimated beam
  - Beam expander + iris to 15 mm (pseudo flat-top)
  - 4-F relay optics
  - 27 % Central Obscuration Emulator (COE)
  - Turbulence phase wheel designed for:
    - 700 mm telescope
    - AO input beam 15 mm
    - Fried Parameter $r_0 = 7.5$ cm ⇨ scaled to $r_0 = 1.6$ mm
  - 2 flat mirrors for beam pointing/centering
  - Power meter + detectors coupled to output SMF-28 single-mode fiber



# Turbulence Simulator

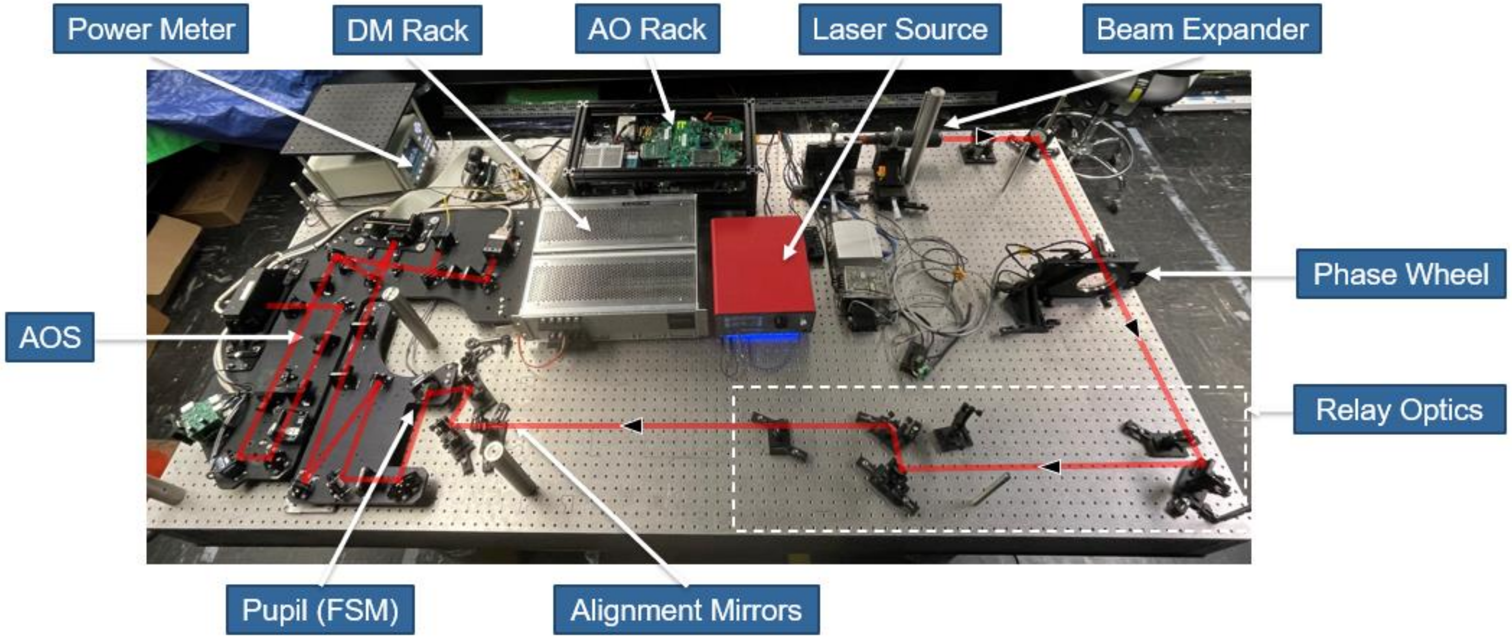
- ❑ Phase plate to simulate atmospheric turbulence in lab
- ❑ Manufactured by Lexitek, inc.
- ❑ Design:
  - ➢ Diameter 83 mm corresponding to a 4096x4096 phase array
  - ➢ Thickness: 22 mm
  - ➢ Fried parameter r0 = 7.5 cm
  - ➢ Beam diameter: 15 mm
  - ➢ Spectral range: 400 - 1600 nm
  - ➢ LS-100 motorized rotary stage:
  - ➢ Greenwood frequency = f (rotation speed)





| Rotation speed (RPM) | Greenwood Freq (Hz) |
|---|---|
| 60.0 | 48.8 |
| 98.4 | 80.0 |
| 120.0 | 97.6 |
| 134.1 | 109.0 |
| 180.0 | 146.3 |
| 184.5 | 150.0 |
| 190.0 | 154.5 |

# 4-F Relay

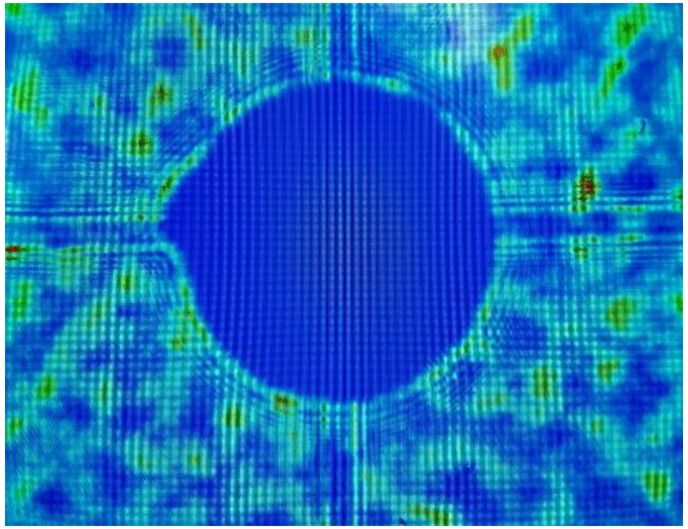


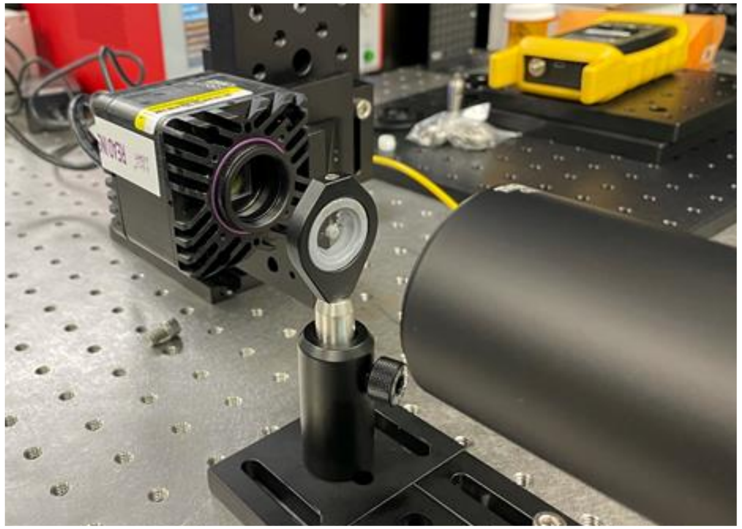

4-F system designed and installed as relay optics to:

- Generate a 15 mm collimated beam
- Reimage phase plate on the AO pupil = tracking FSM
- Wavelength @ 1550 nm +/- 70 nm including O2O and LCRD wavelengths.
- Rytov variance at nominal value of 0.3 + Rytov variance change

# Central Obscuration Emulator

- LCOT AOS installed at the Nasmyth of a 70 cm Ritchey-Chretien telescope
- Secondary mirror mount ⇨ 27% central obscuration
- Central obscuration emulator (COE) to simulate its effect on the AO performance
- 3D printed + metal wires
- Positioned next to the AO pupil (AO tracker FSM)
- 15 mm beam aperture

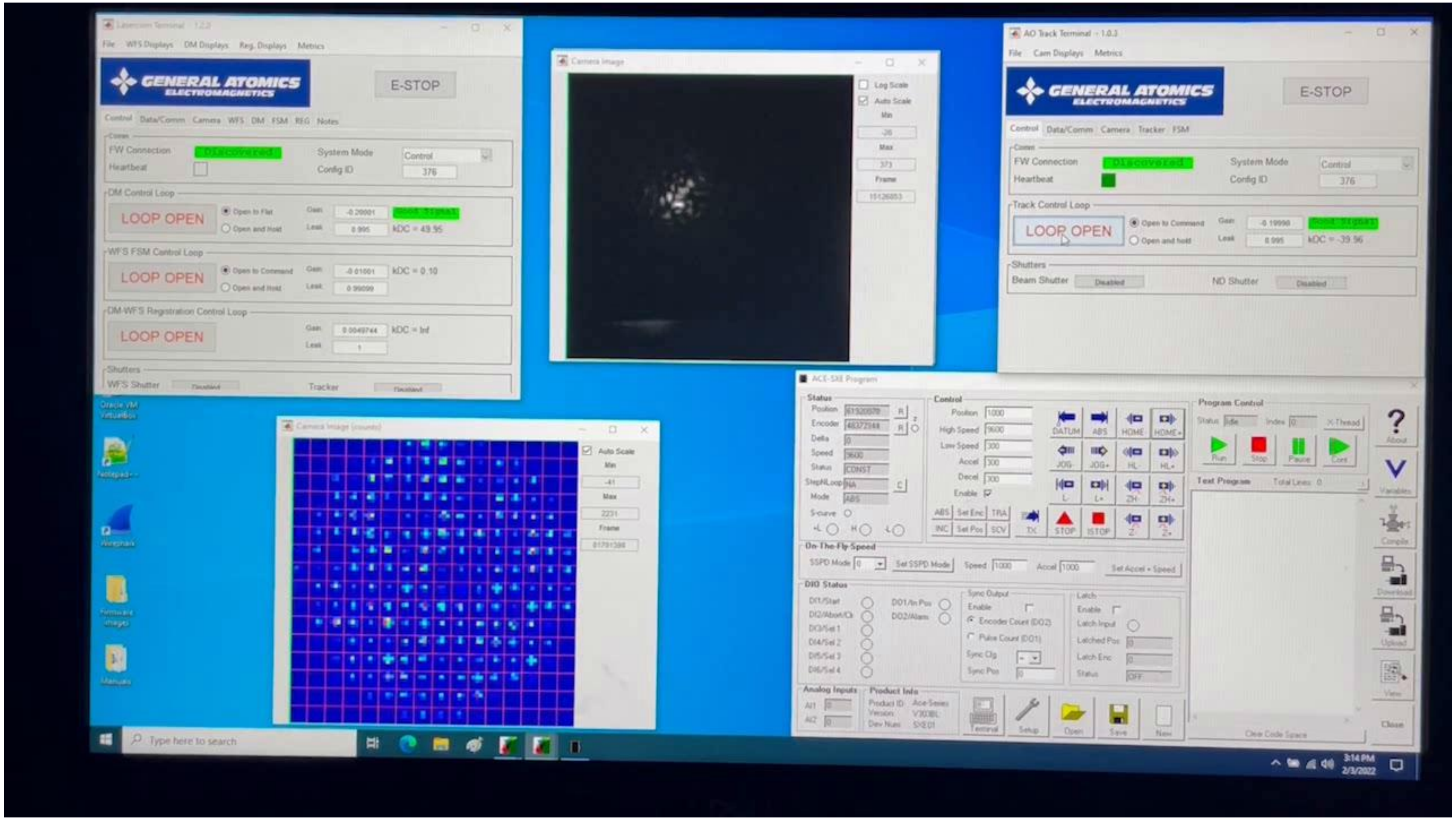




# General Atomics Software

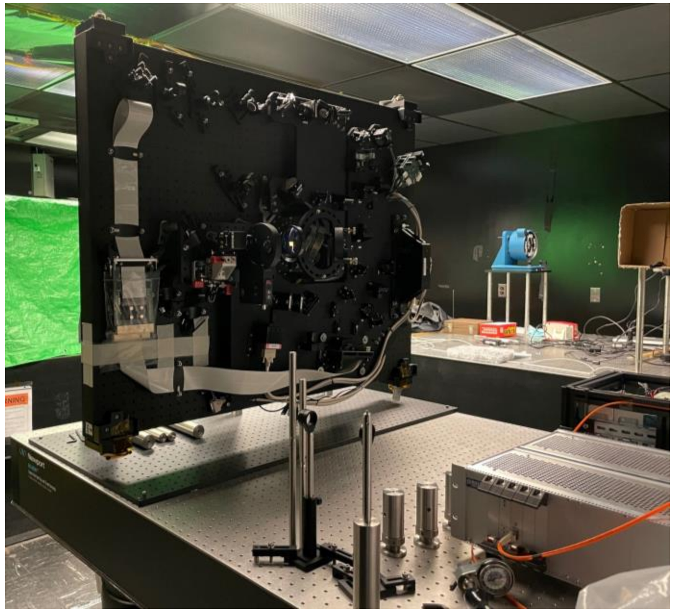
**Test sequence example:**

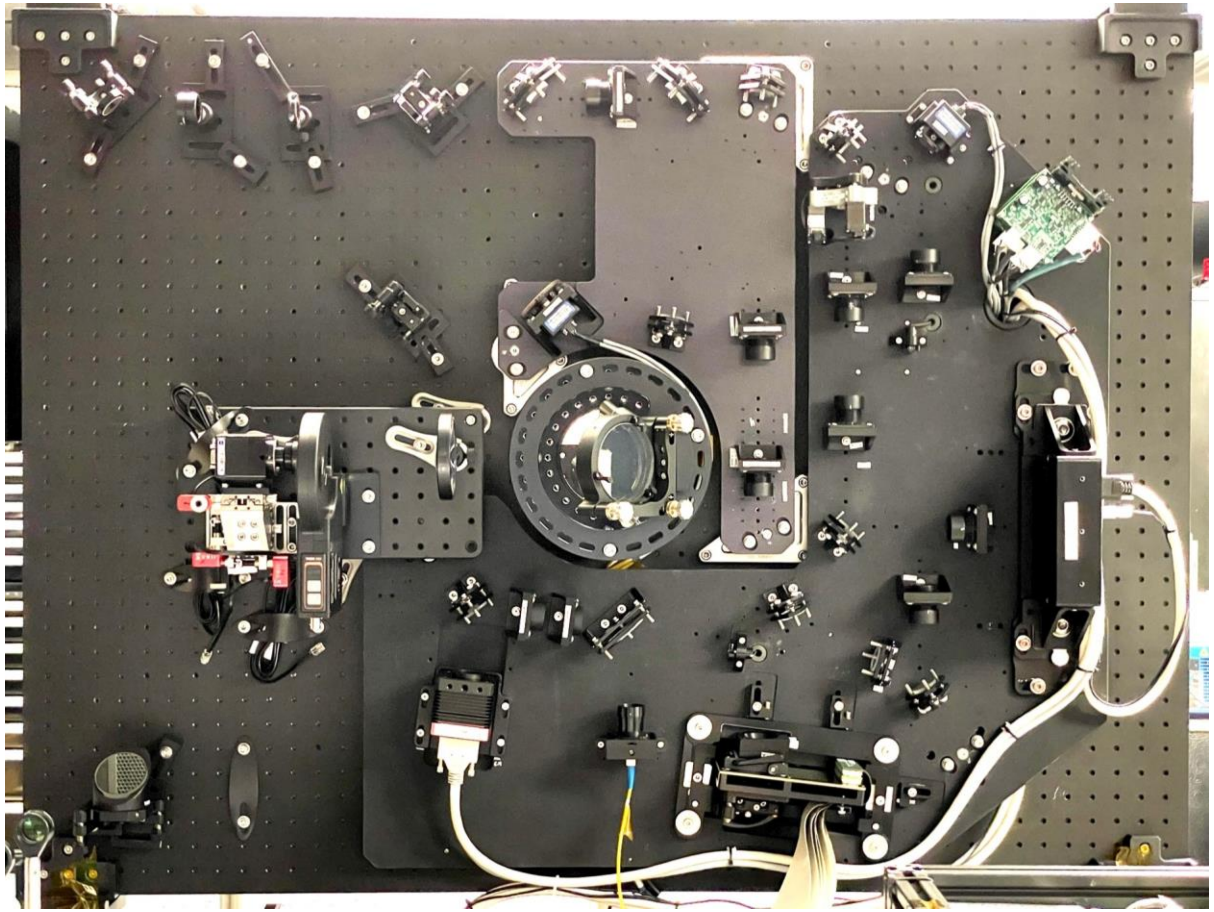
1. AO/Tracker loops open
2. Only Tracker loop closed
3. AO/Tracker loops closed
4. Only AO loop closed
5. AO/Tracker loops closed



# 3 AO System Test Configurations

- ❑ Horizontal test in lab with AO on lab bench
- ❑ Horizontal test in lab with AO on POB
- ❑ Vertical test in lab with AO on POB
  - ➢ Identical test as horizontal
  - ➢ Final test with a telescope simulator



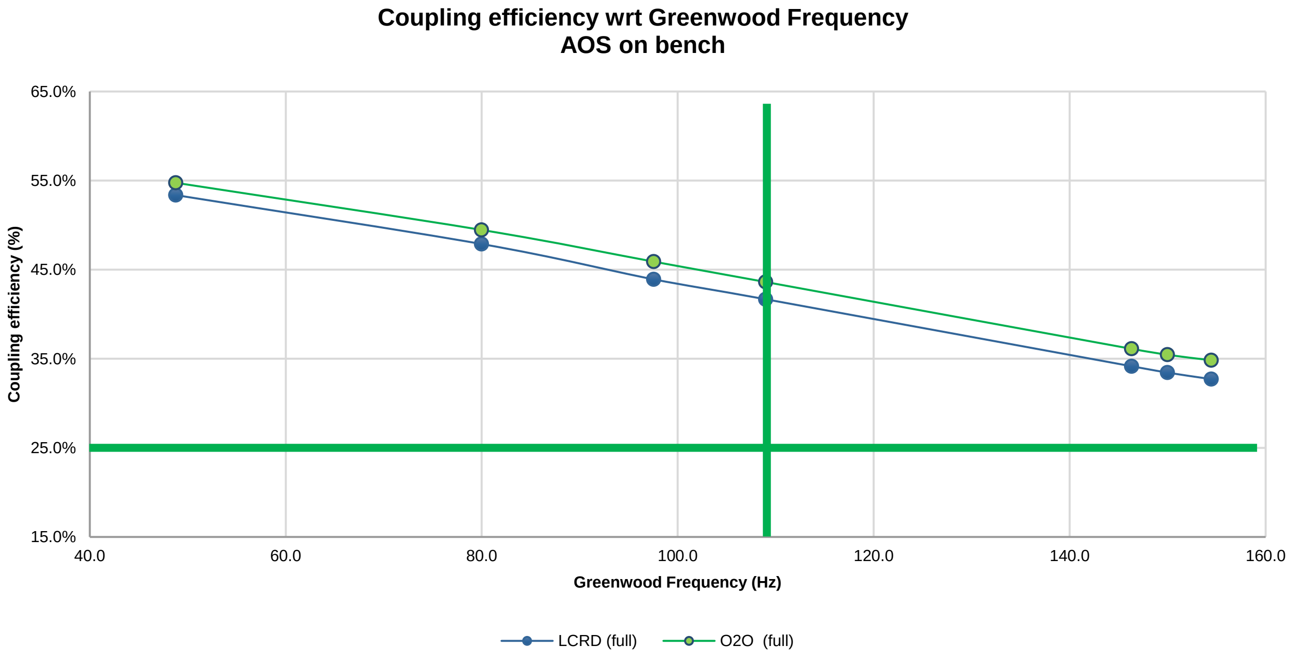


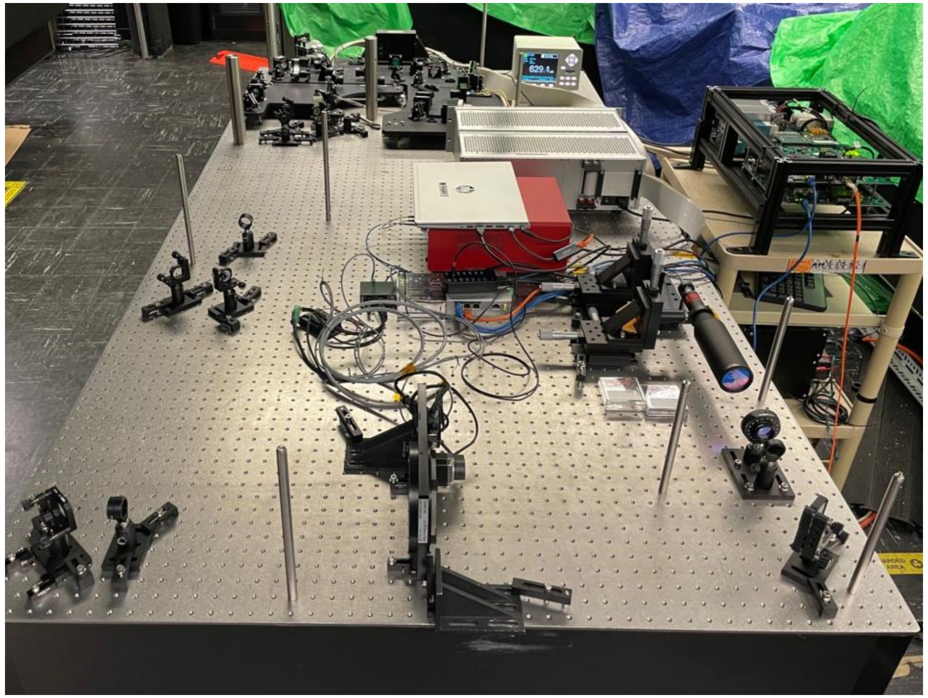
# Preliminary Tests Results

# Coupling Efficiency Vs Greenwood Frequency

**Measurement in GSFC laboratory with AO system on optical bench:**

- Coupling Efficiency > 41.6% @ $f_G$ = 109 Hz



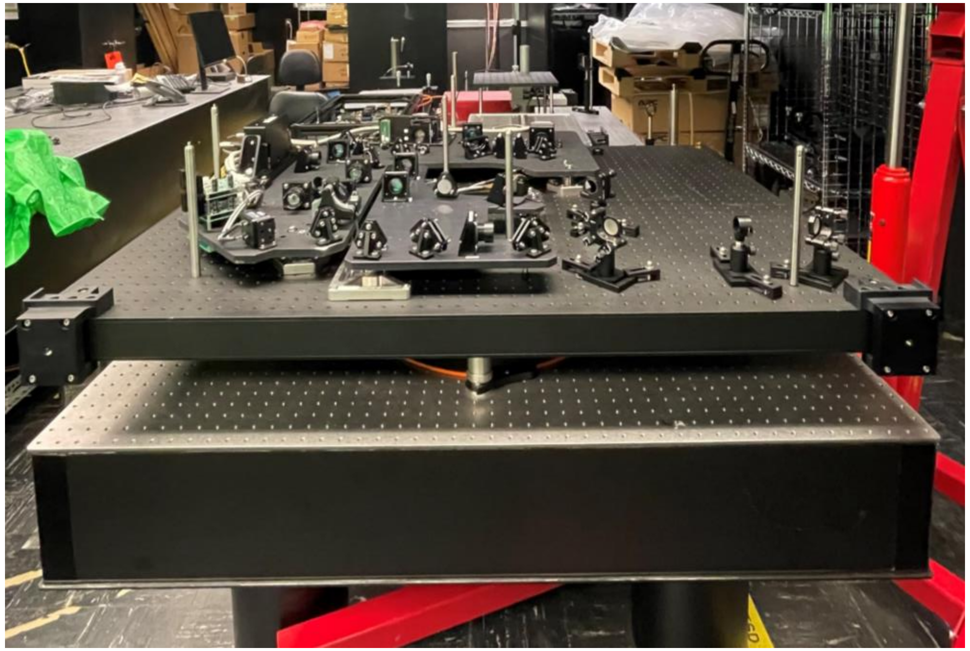



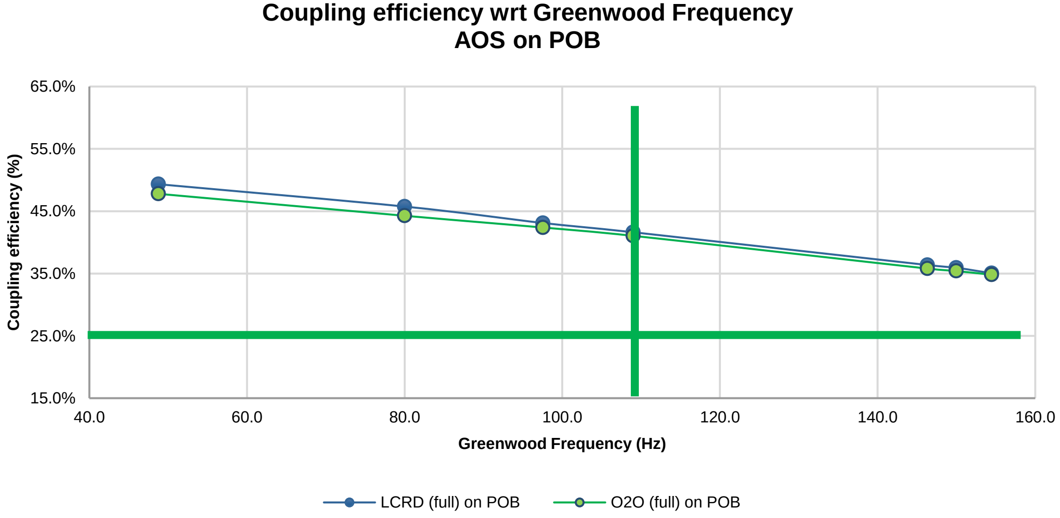
# Coupling Efficiency Vs Greenwood Frequency

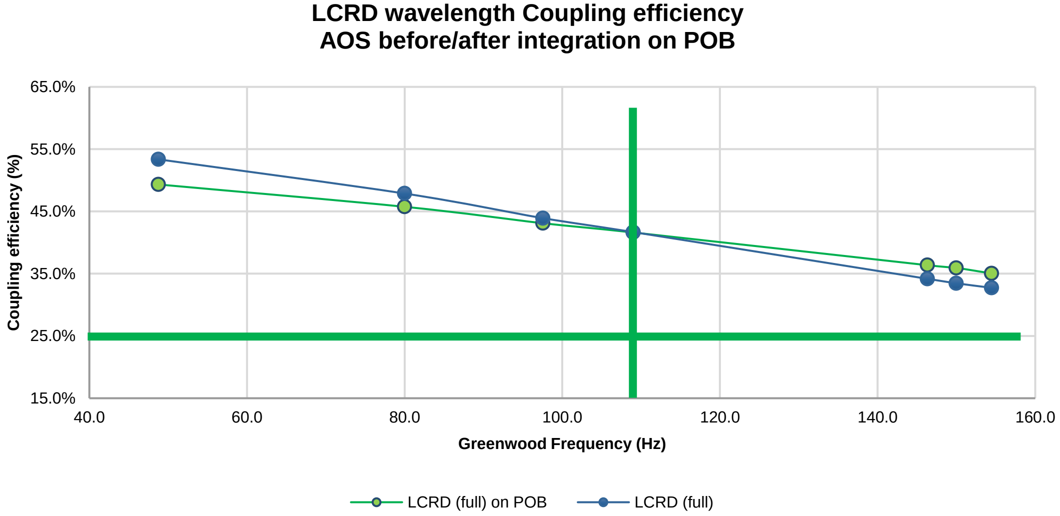
**Measurement in GSFC laboratory with AO system on POB:**

- ❑ Coupling Efficiency> 41.0% @ $f_G$ = 109 Hz

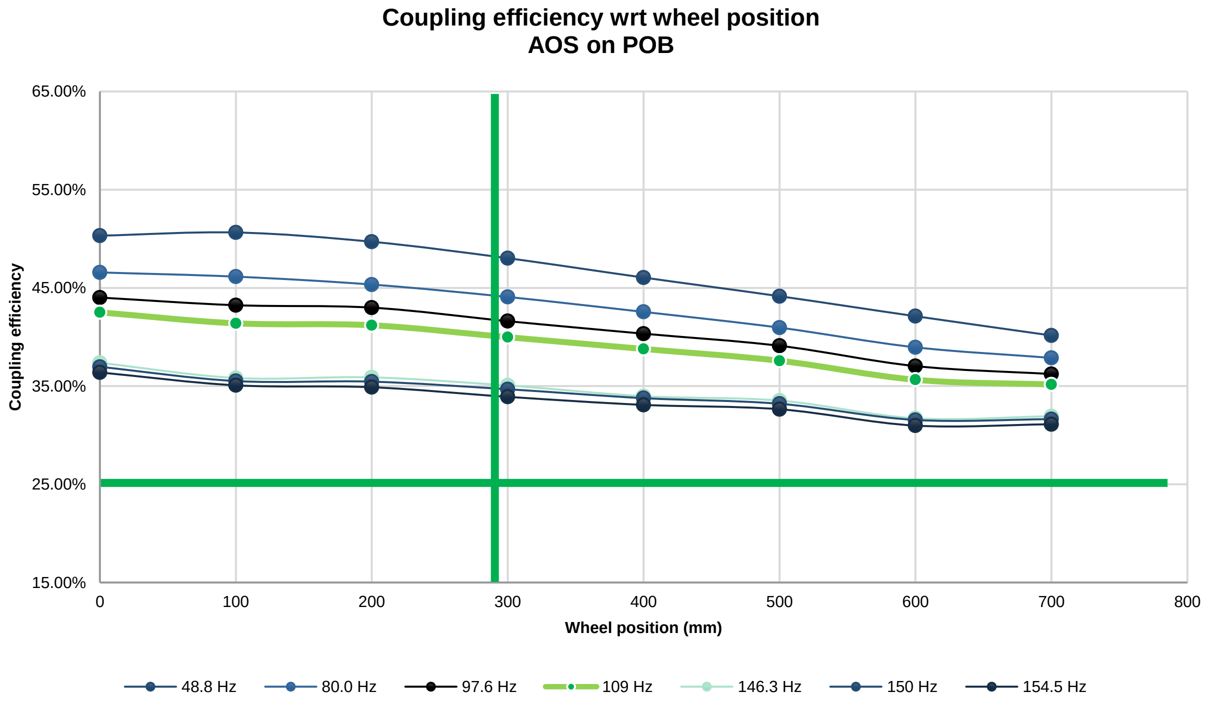
**Maximum repeatability on Coupling Efficiency < 4%**





# Coupling Efficiency Vs Rytov Variance




**Measurement in GSFC laboratory with AO system on POB:**

- ❑ Coupling Efficiency > 33.9% @ position < 290 mm ⇨ Rytov Variance < 0.3 (nominal)
- ❑ Worst case: Coupling Efficiency = 31%

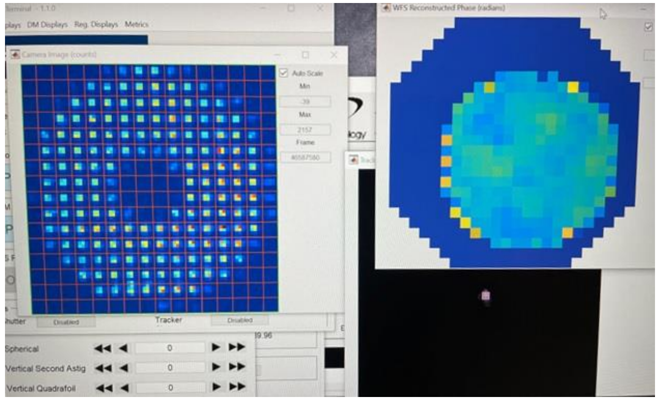
# Central Obscuration Effect

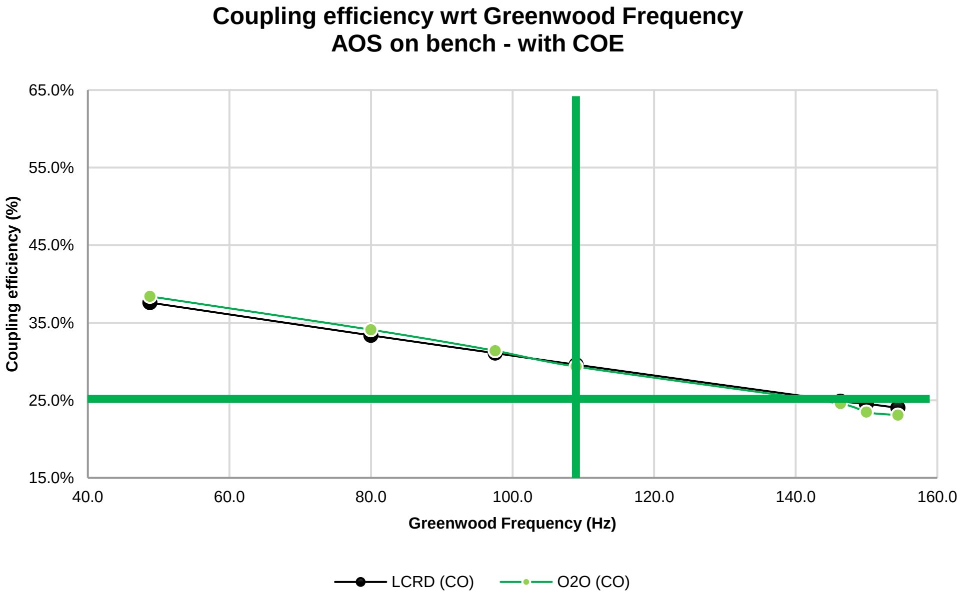
**Measurement in GSFC laboratory with AO system on optical bench:**

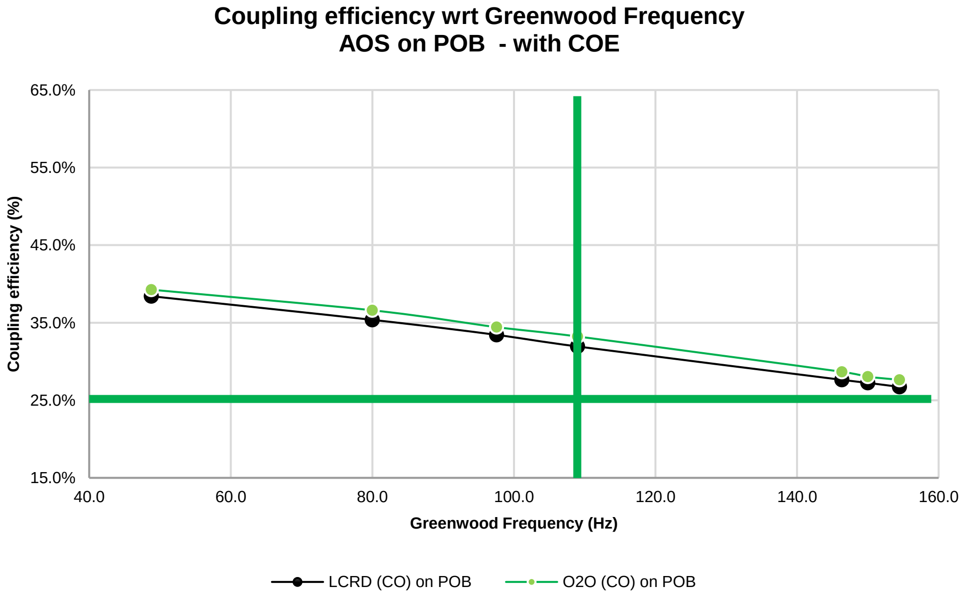
- Coupling Efficiency > 29.3% @ $f_G$ = 109 Hz

**Measurement in GSFC laboratory with AO system on POB:**

- Coupling Efficiency > 31.9% @ $f_G$ = 109 Hz





# Conclusion & Path Forward

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- AO system has been tested in laboratory as individual setup
- Results meet all requirements with and without central obscuration
- On-Sky testing to confirm these data
- Continue AO testing:
  - Vertical position in lab
  - Complete POB test with telescope simulator in lab
  - On-sky: Star + LCRD
- AO system test with LCRD space terminal currently in GEO orbit
- AO system test for future Quantum Communications experiments

# Thank you!